Correlation between X-ray and gamma-ray emission in TeV blazars

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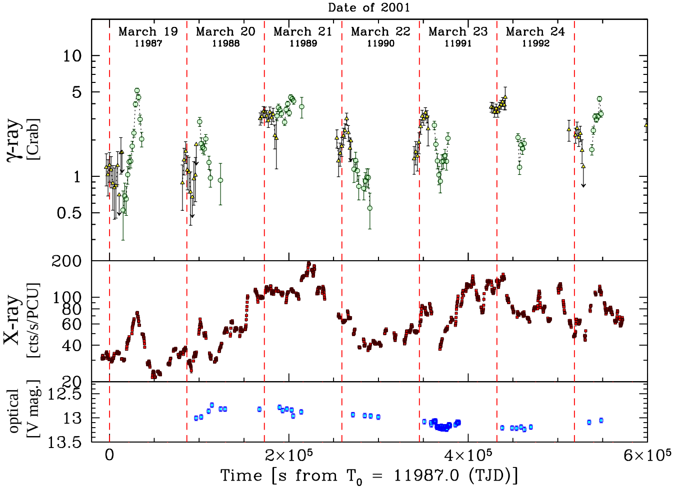
Outline

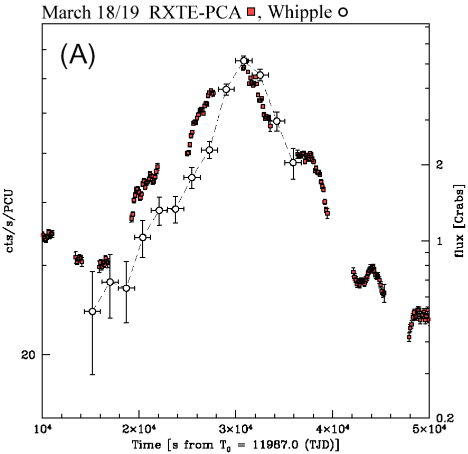
- observations, how we define the correlation
- why simple SSC model does not work
- two or more sources, more complex solution
- conclusions

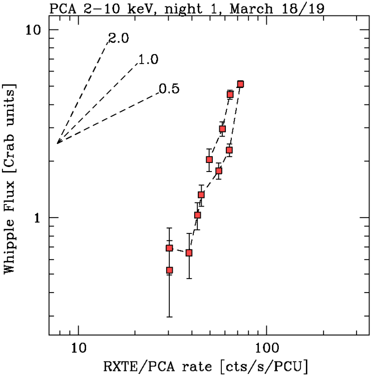
Mrk 421 – optical, X-ray & gamma-ray light curves



TeV – HEGRA & Whipple, X-ray – RXTE-PCA, Fossati et. al. 2008

Mrk 421 – 18/19 March 2001

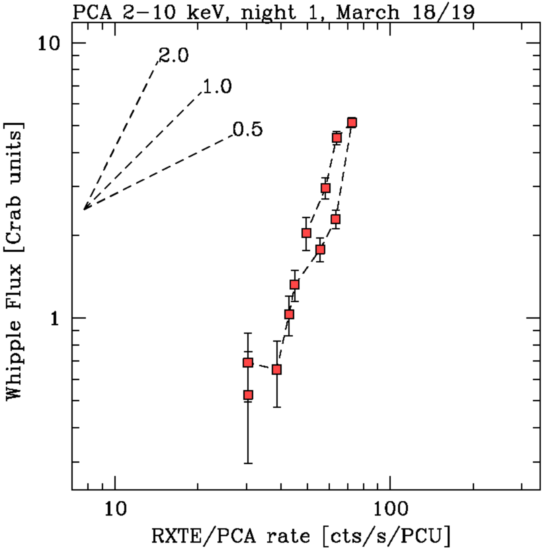




$$F_{\mathrm{TeV}} \propto (F_{\mathrm{X}})^{x\geqslant 2}$$

Fossati et al. 2008

Definition of the correlation



t - time

F - flux

$$F_{\mathrm{X}} \propto t^{s}$$

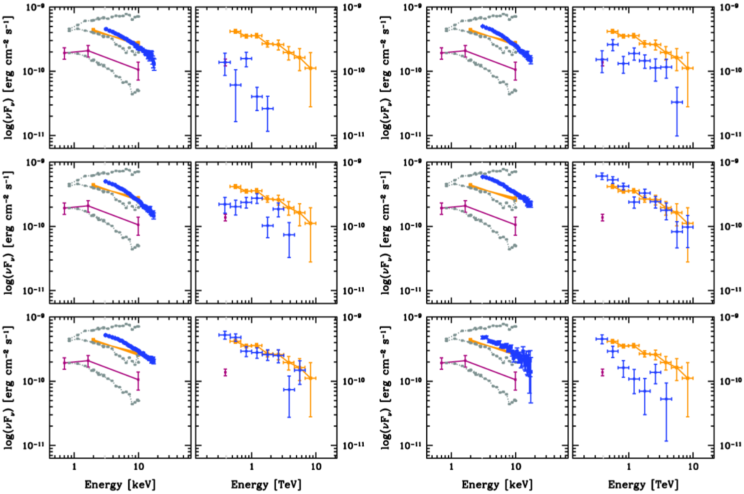
$$F_{\mathrm{TeV}} \propto t^{c}$$

$$t \propto F_{X}^{1/s}$$

$$F_{\mathrm{TeV}} \propto F_{\mathrm{X}}^{c/s}$$

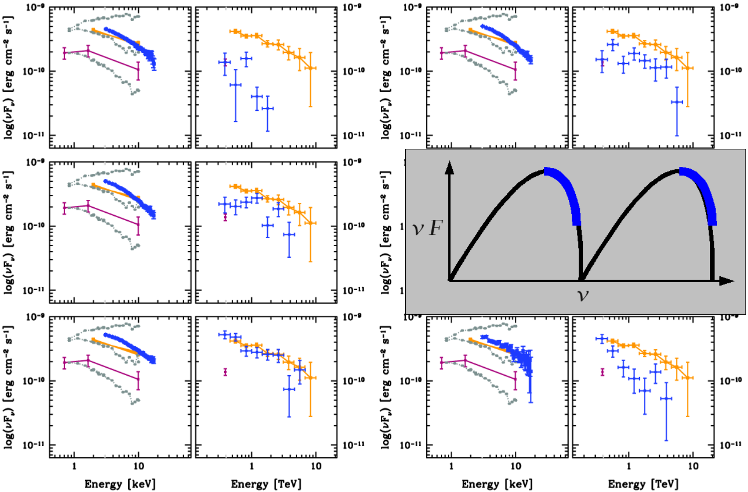
$$x = c/s \geqslant 2$$

Mrk 421 - March 18/19, spectra



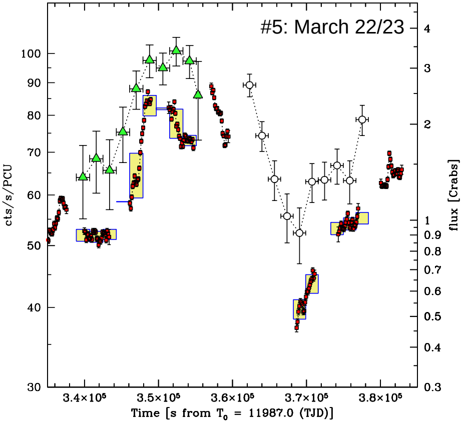
Fossati et al. 2008

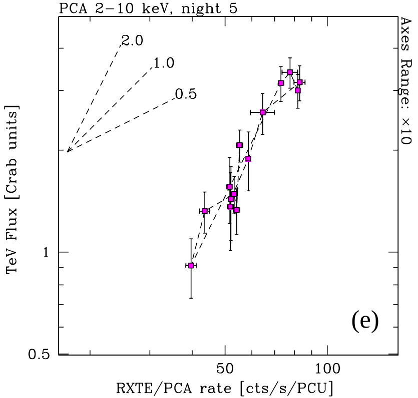
Mrk 421 - March 18/19, spectra



Fossati et al. 2008

Mrk 421 – 22/23 March 2001

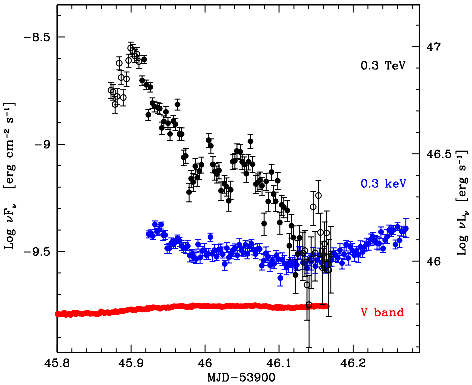




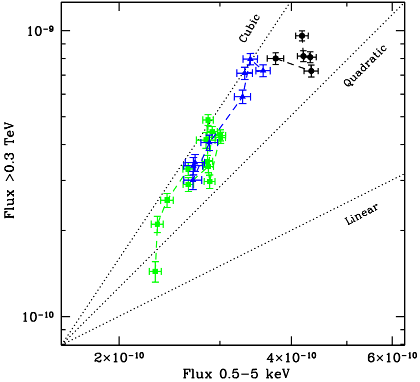
$$F_{\mathrm{TeV}} \propto (F_{\mathrm{X}})^{x \simeq 2}$$

Fossati et al. 2008

PKS 2155-304 – 29/30 July 2006



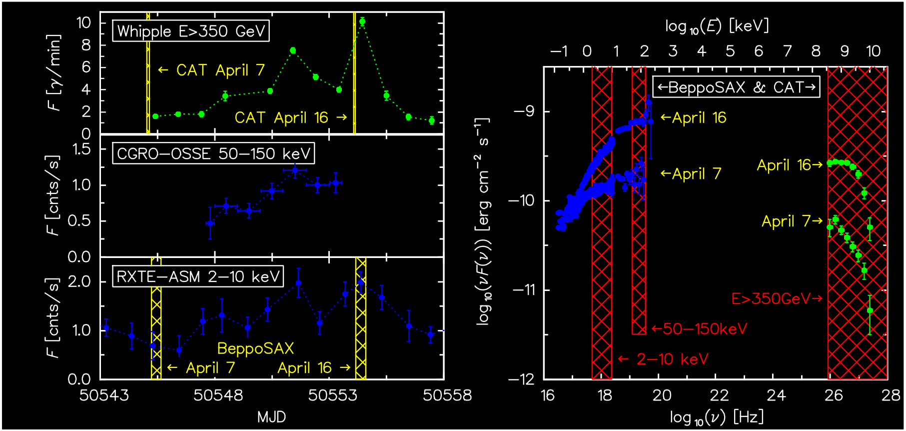
H.E.S.S., Chandra & 32 cm
Bronberg Observatory



$$F_{\rm TeV} \propto (F_{\rm X})^{x\simeq 3}$$

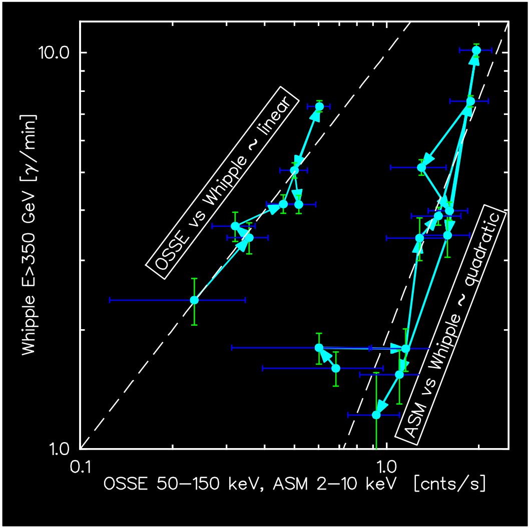
Aharonian et al. 2009 (H.E.S.S. Collaboration)

Mrk 501 - April 1997

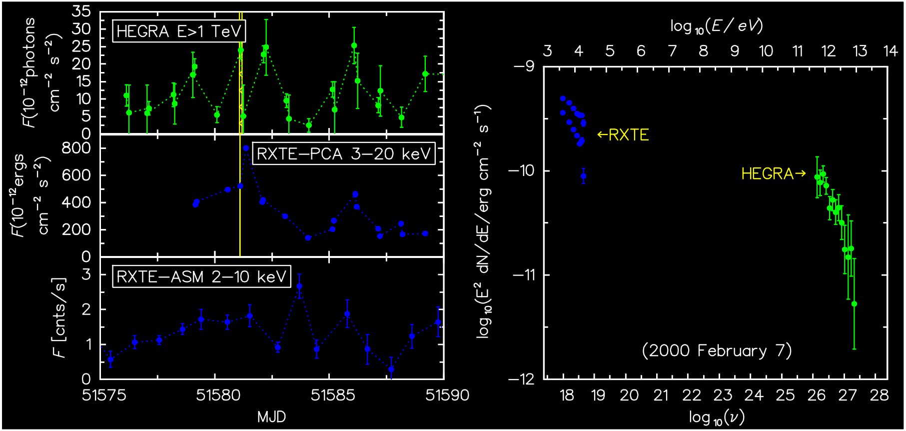


Catanese et al. 1997, Pian et al. 1998, Djannati-Atai et al. 1999

Mrk 501 - correlation for April 1997

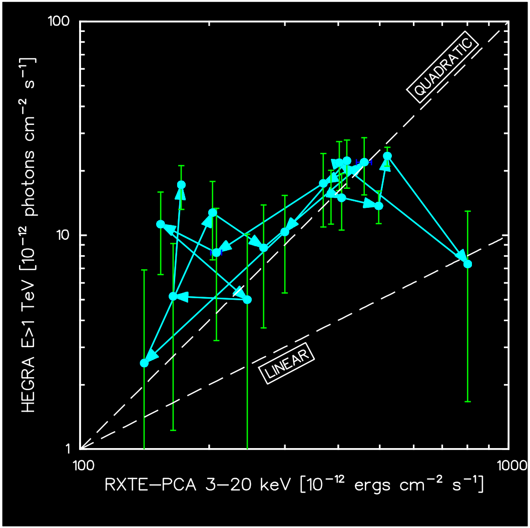


Mrk 421 - February 2000

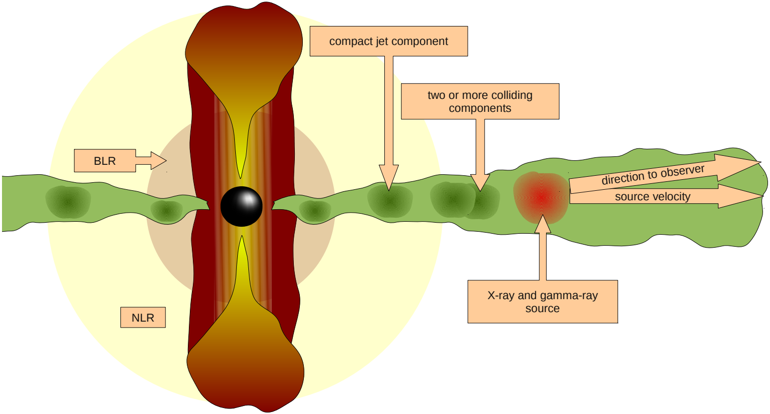


Krawczynski et al. 2001

Mrk 421 - correlation for February 2000



Internal shock scenario



compact jet component

two or more colliding components

BLR

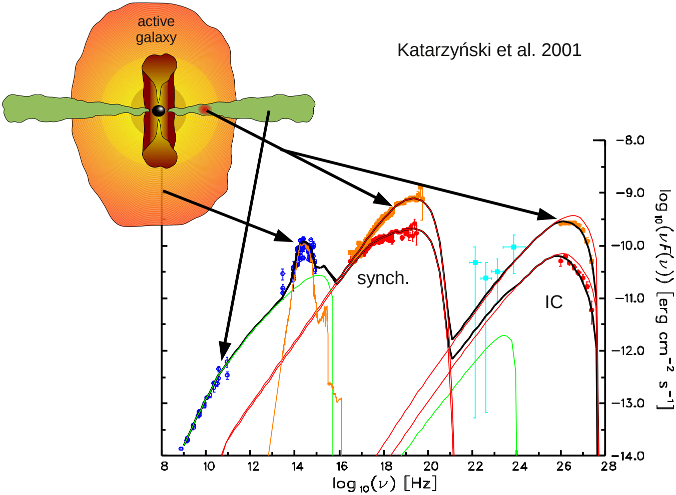
direction to observer

source velocity

NLR

X-ray and gamma-ray source

Mrk 501 – emission model



Homogeneous source - basic assumptions

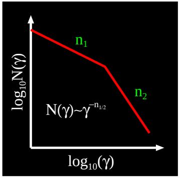
- spherical homogeneous source (R [cm])
- uniform electron density (K [cm^{-3}])
- uniform magnetic field intensity (B [G])
- power law electron energy distribution:

$$N(\gamma) = K\gamma^{-n} \quad \text{for} \quad \gamma_{\rm min} \le \gamma \le \gamma_{\rm max},$$

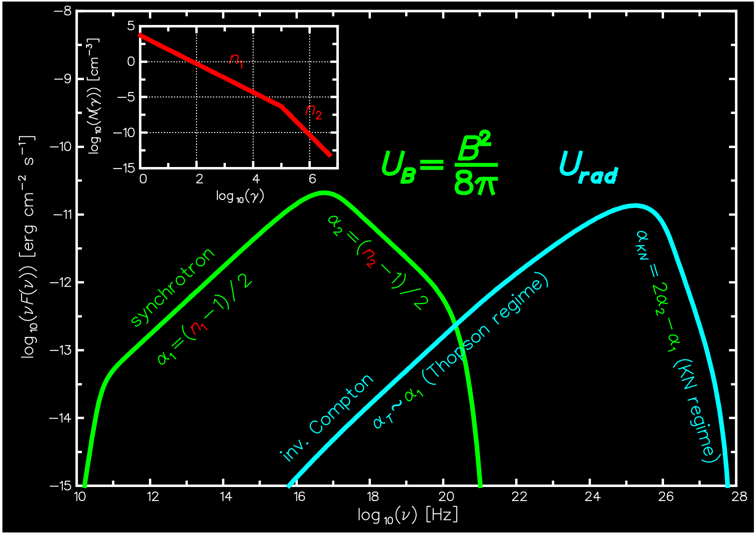
or double (broken) power law distribution:

$$N(\gamma) = \begin{cases} K_1\gamma^{-n_1}, & \gamma_{\rm min} \le \gamma \le \gamma_{\rm brk} \\ K_2\gamma^{-n_2}, & \gamma_{\rm brk} < \gamma \le \gamma_{\rm max} \end{cases}$$

where $E = \gamma m_e c^2$ and $K_2 = K_1\gamma_{\rm brk}^{n_2-n_1}$.



Double power law spectrum



Time dependent SSC - basic assumptions

The evolution of the source radius

$$R(t) = R_0 \left(\frac{t_0}{t} \right)^{-r_{\mathrm{e}}},$$

where R_0 is the initial radius.

The evolution of the magnetic field intensity inside the source

$$B(t) = B_0 \left(\frac{t_0}{t} \right)^{m},$$

where B_0 is the initial magnetic field intensity.

Evolution of electron spectrum

$$N_{\mathrm{e}}(\gamma,t) = \min\left\{N_{\mathrm{e}}^{1}(\gamma,t), N_{\mathrm{e}}^{2}(\gamma,t)\right\}, \text{where}$$

$$N_{\mathrm{e}}^{1}(\gamma,t) = K_{\mathrm{e}}^{1}(t)\gamma^{-n_1}, \qquad N_{\mathrm{e}}^{2}(\gamma,t) = K_{\mathrm{e}}^{2}(t)\gamma^{-n_2}$$

$$K_{\mathrm{e}}^{1}(t) = K_1 \underbrace{\left(\frac{t_0}{t}\right)^{r_{\mathrm{a}}(n_1-1)}}_{\text{adiabatic heating/cooling}} \times \underbrace{\left(\frac{t_0}{t}\right)^{3r_{\mathrm{d}}}}_{\text{density increase/decrease}},$$

$$K_{\mathrm{e}}^{2}(t) = K_2 \underbrace{\left(\frac{t_0}{t}\right)^{r_{\mathrm{a}}(n_2-1)}}_{\text{adiabatic heating/cooling}} \times \underbrace{\left(\frac{t_0}{t}\right)^{3r_{\mathrm{d}}}}_{\text{density increase/decrease}},$$

r_{a} describes the adiabatic losses and r_{d} describes the decrease of the electron density.

Evolution of synchrotron emission

Evolution of the synchrotron flux is described by

$$F_{\mathrm{s}}(t) \propto R(t)^3 K_{\mathrm{e}}(t) B(t)^{m(\alpha+1)},$$

which below the peak gives

$$\begin{aligned} F_{\mathrm{s}}^1(t) &\propto R_0^3 K_1 B_1 \left(\frac{t}{t_0}\right)^{s_1}, \\ s_1 &= 3r_{\mathrm{e}} - 3r_{\mathrm{d}} - r_{\mathrm{a}}(n_1 - 1) - m(\alpha_1 + 1), \end{aligned}$$

and above the peak

$$\begin{aligned} F_{\mathrm{s}}^2(t) &\propto R_0^3 K_2 B_2 \left(\frac{t}{t_0}\right)^{s_2}, \\ s_2 &= 3r_{\mathrm{e}} - 3r_{\mathrm{d}} - r_{\mathrm{a}}(n_2 - 1) - m(\alpha_2 + 1). \end{aligned}$$

Evolution of inverse-Compton emission

Evolution of the inverse-Compton flux below the peak, in the Thompson limit is given by

$$\begin{aligned} F_{\rm c}^{1}(t) &\propto R_0^4 K_1^2 B_1 \left(\frac{t}{t_0}\right)^{c_1}, \\ c_1 &= 4r_{\rm e} - 6r_{\rm d} - 2r_{\rm a}(n_1 - 1) - m(\alpha_1 + 1), \end{aligned}$$

whereas above the peak, in the Klein-Nishina regime we have

$$\begin{aligned} F_{\rm c}^{2}(t) &\propto R_0^4 K_1 K_2 B_1 \left(\frac{t}{t_0}\right)^{c_2}, \\ c_2 &= 4r_e - 6r_d - r_a(n_1 - 1) - r_a(n_2 - 1) \\ &- m(\alpha_1 + 1). \end{aligned}$$

Four basic correlations

we have four basic evolutions:

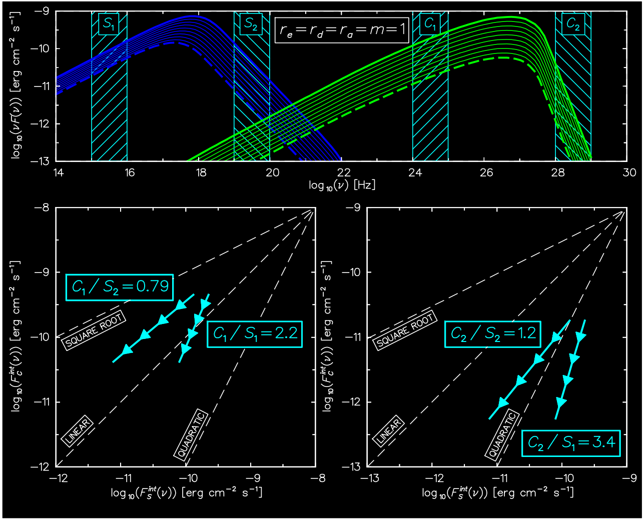
- $F_{\mathrm{s}}^1 \propto t^{s_1}$ for the synch. rad. before the $\nu F_{\mathrm{s}}(\nu)$ peak
- $F_{\mathrm{s}}^2 \propto t^{s_2}$ for the synch. rad. above the $\nu F_{\mathrm{s}}(\nu)$ peak
- $F_{\mathrm{c}}^1 \propto t^{c_1}$ for the IC emission before the $\nu F_{\mathrm{c}}(\nu)$ peak
- $F_{\mathrm{c}}^2 \propto t^{c_2}$ for the IC emission above the $\nu F_{\mathrm{c}}(\nu)$ peak

which give four basic correlations:

$$F_{\mathrm{c}}^1 \propto (F_{\mathrm{s}}^1)^{\mathrm{c}_1/\mathrm{s}_1} \qquad F_{\mathrm{c}}^2 \propto (F_{\mathrm{s}}^1)^{\mathrm{c}_2/\mathrm{s}_1}$$

$$F_{\mathrm{c}}^1 \propto (F_{\mathrm{s}}^2)^{\mathrm{c}_1/\mathrm{s}_2} \qquad F_{\mathrm{c}}^2 \propto (F_{\mathrm{s}}^2)^{\mathrm{c}_2/\mathrm{s}_2}$$

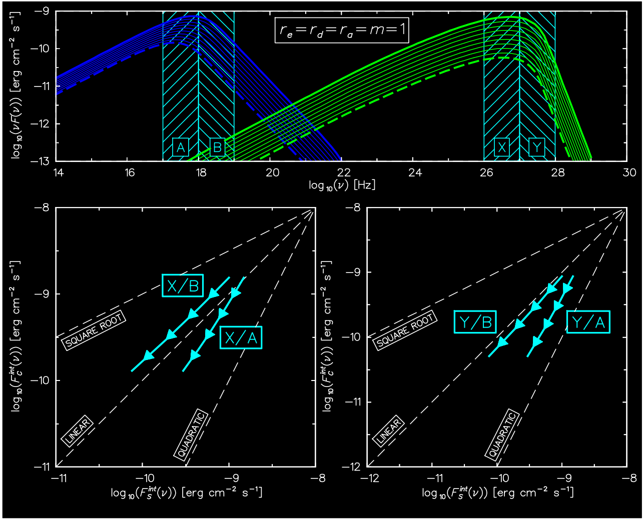
Four basic correlations



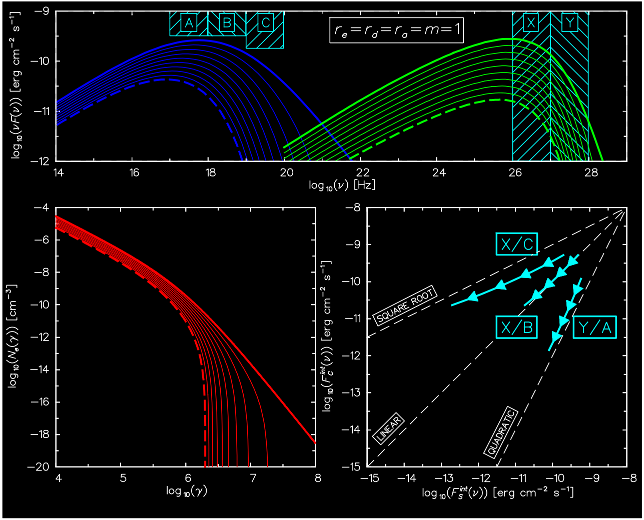
Basic estimations

	r_e	r_d	r_a	m	c_1/s_1	c_1/s_2	c_2/s_1	c_2/s_2
a	1	0	0	0	1.333	1.333	1.333	1.333
b	0	1	0	0	2	2	2	2
c	1	1	0	0	inf	inf	inf	inf
d	1	1	1	0	4	1	7	1.75
e	1	1	1	1	2.2	0.786	3.4	1.214
f	0	0	0	1	1	0.5	1	0.5
g	0	1	1	0	2	1.143	2.75	1.571
h	0	1	1	1	1.727	0.950	2.273	1.250
i	1	1	0	1	2.332	1.167	2.333	1.167
j	1	0	0	1	1.667	inf	1.667	inf
k	0	1	0	1	1.667	1.250	1.667	1.250
l	1	1	1	2	1.75	0.7	2.5	1

Correlations around the peaks



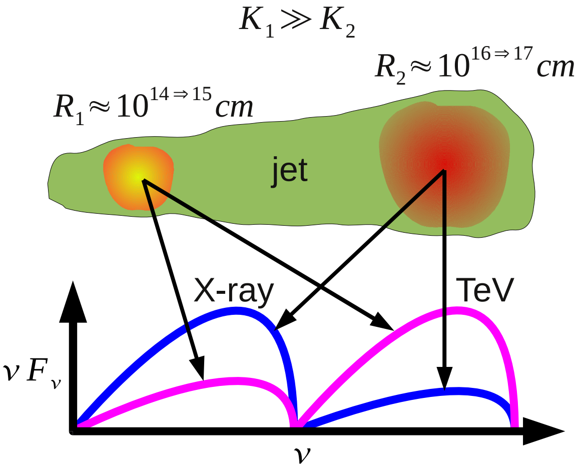
Impact of the radiative cooling



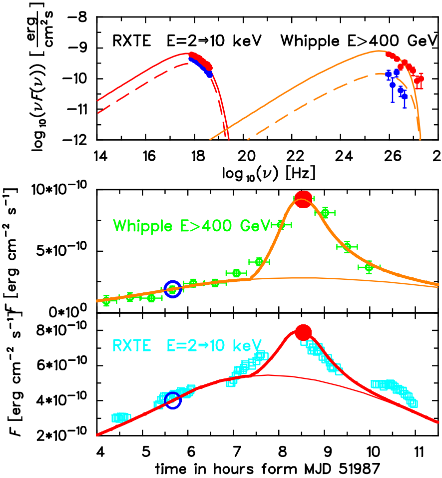
Simple SSC model cannot explain observed correlations

- An injection of the relativistic particles into the source that increases the density could in principle explain the quadratic correlation during rising phase of a flare. However, this requires $R = \mathrm{const.}$, $B = \mathrm{const.}$ and negligible radiative cooling during the injection.
- By analogy to the injection, systematic energy independent escape of the particles that decreases the density could in principle explain the quadratic correlation during decay phase of a flare. However, the particles outside the source can still produce efficiently gamma rays through the inverse-Compton scattering. In other words the gamma-ray emission will not decay fast enough to produce the quadratic correlation during the decay phase.
- What about observed more than quadratic correlations?

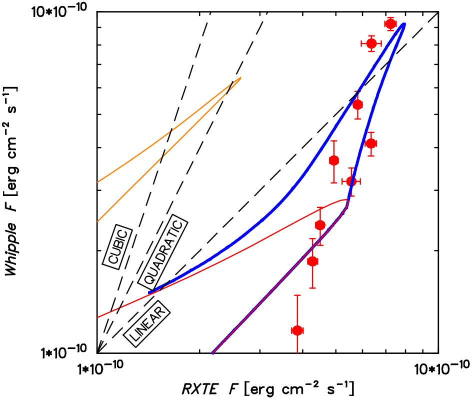
Emission of two sources at the same time



Mrk 421 – variability of two sources



model → injection & cooling



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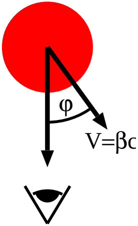
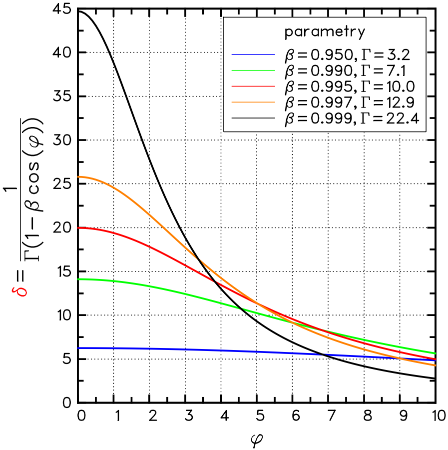
Doppler boosting effect

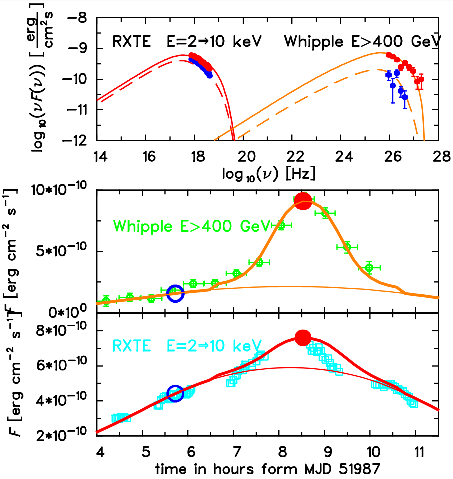


transformations of:

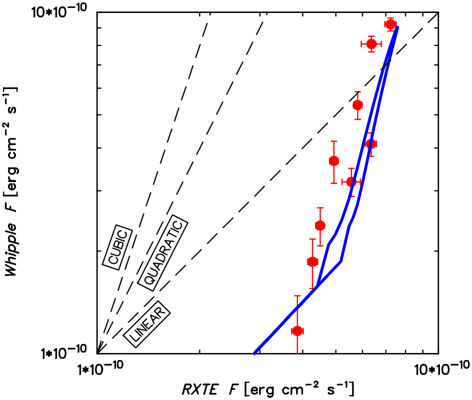
- time
  $t = (1+z)t'/\delta$
- frequency
  $\nu = \frac{\delta}{1+z}\nu'$
- intensity
  $I_\nu = \delta^3 I'_{\nu'}$



Mrk 421 – variability due to the change of φ



model – $\varphi(t) \longrightarrow \delta(t)$



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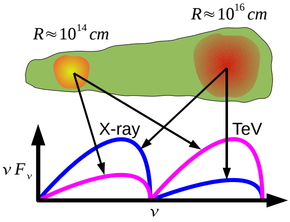
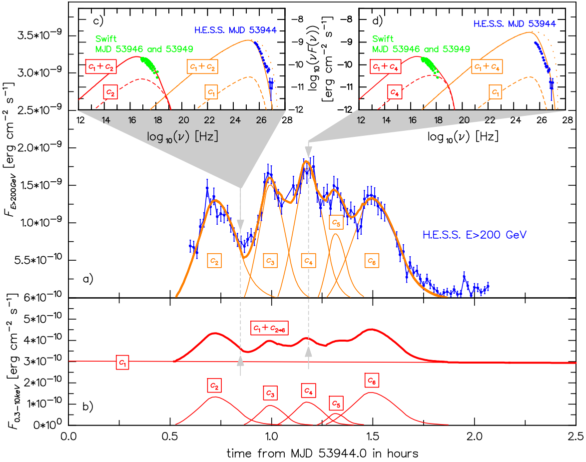
PKS 2155-304 – very rapid variability





Katarzyński et al. 2008

Conclusions

The proposed approach has several advantages:

- it can explain any slope of the correlation,
- in the extreme case it is possible to explain the orphan flares,
- the approach does not involve a new model of the emission, it uses the standard SSC scenario to explain a single source radiation,
- it may explain why the correlation was well determined only in a few cases so far,
- in was already shown that using this approach it is possible to explain also the rapid variability.

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